

# **Inversion for Geoacoustic Model Parameters in Range-Dependent Shallow Water Environments from the SW06 Experiment**

N. Ross Chapman  
School of Earth and Ocean Sciences  
University of Victoria  
PO Box 3055  
Victoria, B.C. V8W 3P6  
phone: (250) 472-4340 fax: (250) 472-4620 email: [chapman@uvic.ca](mailto:chapman@uvic.ca)

Award Number: N0001403-1-0131 / Shallow-water acoustics

## **LONG TERM GOALS**

The ability to predict sound propagation in shallow water is limited by the knowledge of the geoacoustic properties of the ocean bottom. The long term goals of this research are: (1) to investigate full field inversion methods for estimating parameters of geoacoustic models of the ocean bottom and the associated uncertainties in the model parameter values; and (2) to evaluate the performance of the geoacoustic inversion techniques for applications over a broad frequency band in range dependent shallow water environments. This work is set within the wider context of research to determine the impact of the interaction of sound with the ocean bottom in sound transmission in shallow water.

## **OBJECTIVES**

The recent ONR-sponsored research program in benchmarking geoacoustic inversion methods has demonstrated the maturity of present-day inversion methods against synthetic data for range-dependent shallow water environments (Chapman et al, 2003). A critical unresolved issue is the evaluation of the performance of the inversion methods for estimating geoacoustic profiles from real data at sites where the ground truth about the ocean bottom environment is well known. The experiments carried out in the ONR SW06 Experiment during August-September 2006 on the New Jersey continental shelf have provided high quality data over a broad frequency band from 50 Hz to 20 kHz that can be used for evaluating and comparing the performance of several different techniques. These include most notably matched field inversion, reflection coefficient and bottom loss inversion, phase and group velocity dispersion and wavenumber extraction inversions.

Although the matched field inversion methods have proven to be very effective in many experimental scenarios, there is a remaining question of how well the methods perform in the presence of unknown variations of the environmental parameters. Effects due to spatial variations in the ocean bottom parameters such as water depth and sediment sound speed have been investigated in various numerical simulation studies (e.g. Morley et al., 2008). However, uncertainties in the water sound speed will also affect the inversion performance, because the matched field methods are based on acoustic propagation models that require information about the sound speed profile in the water to predict the replica fields. Uncertainties in the water sound speed can arise due to internal waves, eddies, fronts and tidal currents that generate local inhomogeneities in the water at different spatial and temporal scales.

The overall objectives in this proposal are based on use of the low and mid frequency data (50 Hz to 4.5 kHz) obtained in the SW06 experiment: (1) Evaluate the performance of low frequency (< 1 kHz)

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2008</b>		2. REPORT TYPE <b>Annual</b>		3. DATES COVERED <b>00-00-2008 to 00-00-2008</b>	
4. TITLE AND SUBTITLE <b>Inversion For Geoacoustic Model Parameters In Range-Dependent Shallow Water Environments From The SW06 Experiment</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>University of Victoria,School of Earth and Ocean Sciences,PO Box 3055,Victoria, B.C. V8W 3P6,</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>Code 1 only</b>					
14. ABSTRACT <b>The ability to predict sound propagation in shallow water is limited by the knowledge of the geoacoustic properties of the ocean bottom. The long term goals of this research are: (1) to investigate full field inversion methods for estimating parameters of geoacoustic models of the ocean bottom and the associated uncertainties in the model parameter values; and (2) to evaluate the performance of the geoacoustic inversion techniques for applications over a broad frequency band in range dependent shallow water environments. This work is set within the wider context of research to determine the impact of the interaction of sound with the ocean bottom in sound transmission in shallow water.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>9</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

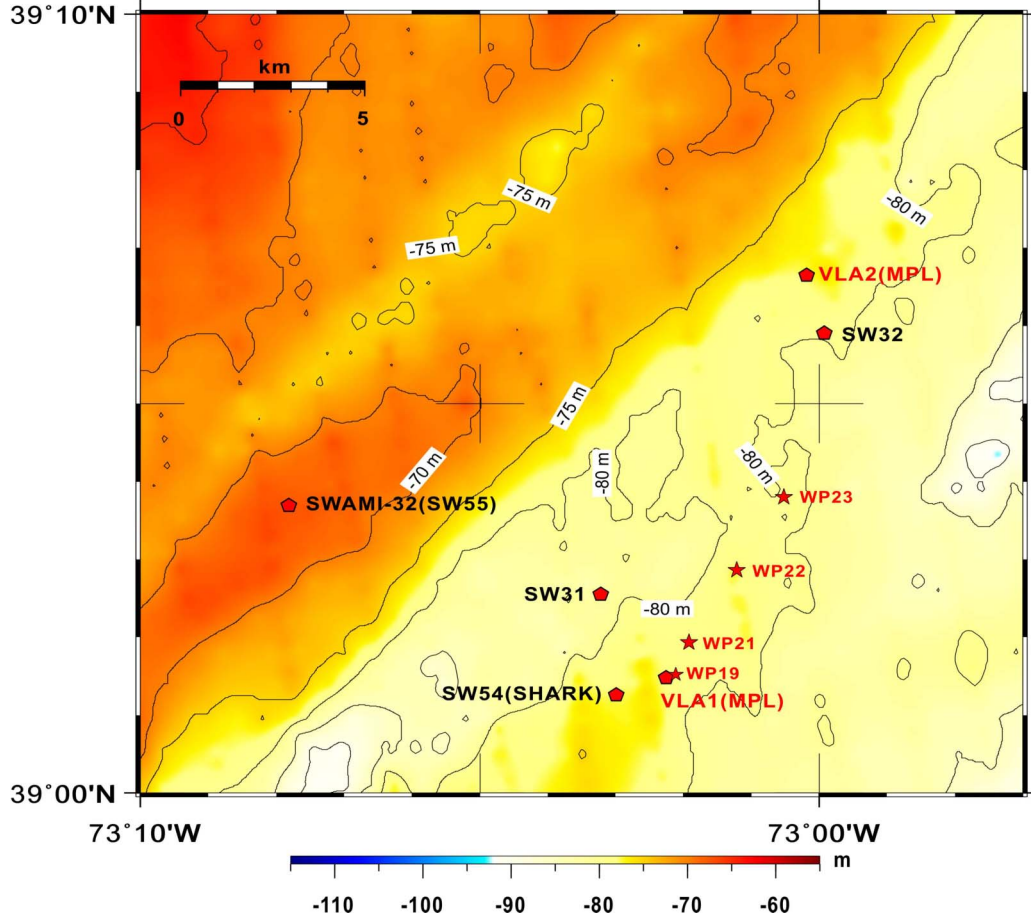
matched field geoacoustic inversion for estimating geoacoustic models in a range dependent continental shelf break environment; (2) Determine the impact of uncertainties in the water column sound speed profile (due to volume inhomogeneities in the water column) on geoacoustic inversion, and develop effective ways to account for the uncertainties in the inversion; (3) Investigate methods for geoacoustic inversion in the mid frequency band (1 – 5 kHz); (4) Determine the geoacoustic model parameters that are most critical for predicting sound propagation over the LF and MF bands. The research described here addresses the first three objectives that are listed above.

## APPROACH

The research makes use of data recorded on the Marine Physical Laboratory vertical line arrays in collaborative SW06 experiments with Drs. W. S. Hodgkiss and P. Gerstoft. These data provide the means to evaluate the performance of inversion methods in short and long range experimental geometries, and interpret the estimated model parameters in terms of physical properties of the bottom materials, particularly, the frequency dependence of sound speed and attenuation in the sediment. The research is based on Bayesian matched field inversion of the low frequency data, and on ray theory inversion of the mid frequency data.

**Description of the Experiments:** The data used in this paper were recorded on a bottom-moored vertical line array deployed by Dr. Hodgkiss and his research group. The shelf break location (Fig. 1) was specifically chosen to amplify the impact of uncertainties in the water sound speed profile on geoacoustic inversion performance due to internal waves, the shelf break front, a salinity/density and current that meanders near the shelf edge, and the frequent presence of warm-core eddies shed from the Gulf Stream. The location was also the site of high frequency acoustic measurements (2–20 kHz) that were done prior to the low frequency experiments (Choi et al, 2008; Jie et al, 2008), and extensive chirp sonar (2–12 kHz) surveys of the sub-bottom by Dr A. Turgut (Turgut and Yamamoto, 2008) prior to the VLA deployment. The vertical array consisted of 16 hydrophones equally spaced at 3.75 m, with the bottom-most sensor 8.2 m above the sea floor. A J-15 sound projector was used to generate low frequency signals in one of three modes: a set of CW tones, either four tones from 53 to 253 Hz, or five tones from 303 to 953 Hz; or an LFM sweep from 100–900 Hz. Mid frequency signals over the band 1.5–4.5 kHz were generated by a separate sound source that was used at the completion of the low frequency experiments.

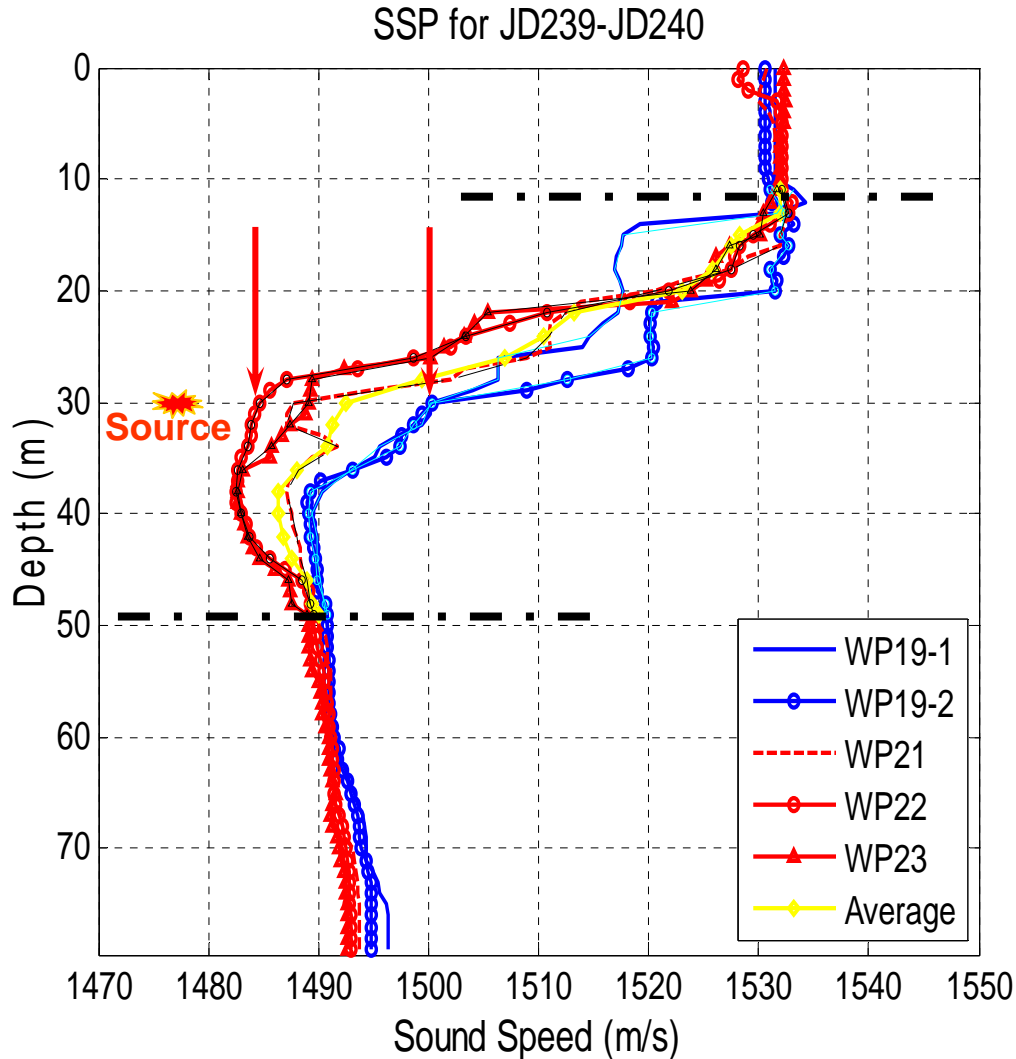
**Low Frequency data:** This report focuses on the analysis of data from a radial track from the vertical array out to ~8 km along one of the chirp survey lines. The source ship stopped at stations of 1, 3, 5 and 7 km (WP21-23 in Figure 1) and transmitted the CW tone sequences for about five minutes, at a source depth of 30 m. The water depth was range independent out to about 3 km, and gradually increased to about 83 m over the remainder of the track. Sound speed profiles (SSPs) measured in the water at each station indicated that the variation was significant over relatively short time scales and distances, due to the proximity of the shelf break (Figure 2). The high resolution chirp sonar survey revealed well-resolved structure down to about 30 m along the radial track, most prominently showing the ‘R’ reflector at about 20 m. This interface, which is pervasive in the region, was overlaid with alternating layers of sand and mud. In situ sediment probes were also deployed at selected sites (Jie et al, 2008). The preliminary analysis of these data indicated a sound speed value of around 1620 m/s for the sea floor sediments near the vertical array. However, the sea floor sediment type varied significantly over the region, most notably at 10-20 km sand ridges roughly parallel to the shelf break.



*Figure 1. Location of the experiments (VLA1) on the New Jersey Shelf.*

The low frequency inversion method is based on Bayes rule that relates conditional probabilities of the measured data and possible ocean bottom models that are within a set of bounds for the geoacoustic model parameters. The Bayesian solution combines prior knowledge about the model parameters with the information about the parameters that is contained in the data. The method accounts for mismatch between the measured data and calculated replica fields due to uncertainties in the ocean environment by estimating a data error covariance matrix. The covariance matrix is estimated from an ensemble of data windows that contain the data error information, following a method developed previously in our research program (Jiang, Chapman and Badiy, 2007). The uncertainty in the water column sound speed is accommodated by inverting for the parameters of an ‘average’ sound speed profile that is defined by a set of empirical orthogonal functions (EOFs). Two approaches for designing the EOFs are considered. The first one uses only the variations in the SSPs that were observed during the time of the experiment. The second one includes SSPs measured at other times and sites in the vicinity to capture a wider degree of variation of the profile. In both approaches, the EOFs described only the variation in the thermocline; as seen in Figure 2, there is very little variation at depths above and below the transition layer. The geoacoustic model consisted of a sediment layer over a half space. The sediment was modelled as an inhomogeneous sound speed layer, with constant density and attenuation. However, the attenuation and density of the half space were held at constant values. In addition, geometric parameters of the experimental configuration and the EOF coefficients were also estimated.

**Mid frequency data:** An experiment was carried out at very short range (230 m; WP 19 in Figure 1) from the VLA to determine high resolution structure of the geoacoustic model. The source was lowered in the water from 25 m to 65 m in 10 m steps. The source transmitted a 1-s sweep signal over the mid-frequency band for 5 minutes at each depth. The match-filtered signal revealed sub-bottom reflectors from the R-reflector and a weaker reflector at a shallower depth. The travel times of the sub-bottom arrivals were inverted using ray theory to estimate the average sound speed and depths to the reflecting interfaces.



**Figure 2.** Sound speed measurements at the receiver (WP 19) and at the source (WPs 21-23) during the experiment. The sound speed at the source varies by ~18 m/s.

## WORK COMPLETED

Matched field inversions were carried out for the low frequency data from the experiments at 1, 3 and 5 km ranges. An inversion method was developed based on ray theory to invert the travel time

differences of the bottom and sub-bottom arrivals, and the travel time inversions were completed for the short-range variable-depth experiment at the VLA central site.

## RESULTS

**Low Frequency inversions:** The estimated values for the geoacoustic parameters from the 1-km range data are displayed in the panels shown in Figure 3. The group of panels in Figure 3(a) show the Bayesian marginal densities that were obtained for the inversion using only a limited set of SSPs to construct the EOFs, and the group in Figure 3(b) show the results for the more extensive SSP set. At this range, the inversion is most sensitive to the sound speeds in the upper layer of sediment and the sound speed in the basement layer below the R-reflector. The inversion indicates a thickness of about 22 m for the layer, consistent with the expected depth of the ‘R’ reflector from the chirp sonar survey. Within the layer, the sound speed decreases from a value of 1640 m/s at the sea floor to around 1580 m/s at the base of the layer. The sound speed increases to about 1800 m/s across the interface at the base of the sediment layer. In comparison with ground truth data, the preliminary analysis of measurements of sediment sound speed at the sea floor from the in situ probes near the vertical array indicate sound speeds of ~1620 m/s. The variation with depth within the layer is consistent with results from deeper cores in the vicinity that show decreasing sound speed at depths between 3-15 m due to embedded layers of clay and silt. The sound speed increase at the ‘R’ reflector is between 1750-1850 m/s.

Comparison between similar panels in Figures 3(a) and (b) indicates that including a greater degree of variation in the water column SSPs to construct the EOFs did not have a significant impact on the geoacoustic parameter estimates. However, the computational efficiency of the inversion is significantly reduced for the inversion with the larger SSP set because a greater number of EOF coefficients was required to account for the greater variation in the SSPs. In addition, two dimensional marginal densities showed that there was little or no correlation between the most sensitive EOF coefficients and the geoacoustic parameters.

The other geoacoustic parameters are not well estimated in this experiment, as judged by the large spread of values in the marginal densities. A matched field inversion is sensitive to attenuation in the sediment by means of the loss in energy in the propagated field. In this inversion, attenuation is assumed to be a general loss parameter that could include effects of scattering and intrinsic absorption of sound in the sediment. It is modelled as  $\alpha t^\beta$ , where  $\alpha$  is the attenuation in dB/m at 1kHz, and  $\beta$  is a constant. As seen in Figure 3, the experiment is not sensitive to attenuation at a range of 1 km.

### **Mid Frequency inversions:**

The matched filtered signals for one-minute averages of data for source depths of 25, 35, 55 and 65 m are shown in Figure 4. The arrival from the sub-bottom reflector is seen at times following the bottom reflected path (BR). The results of the travel time inversions are listed in Table 1. The estimated values of depth to the reflector and the average sound speed from the time data are in good agreement with the estimates from the full field inversion. The short-range mid frequency data provide higher resolution of the structure, as indicated in Table 2.

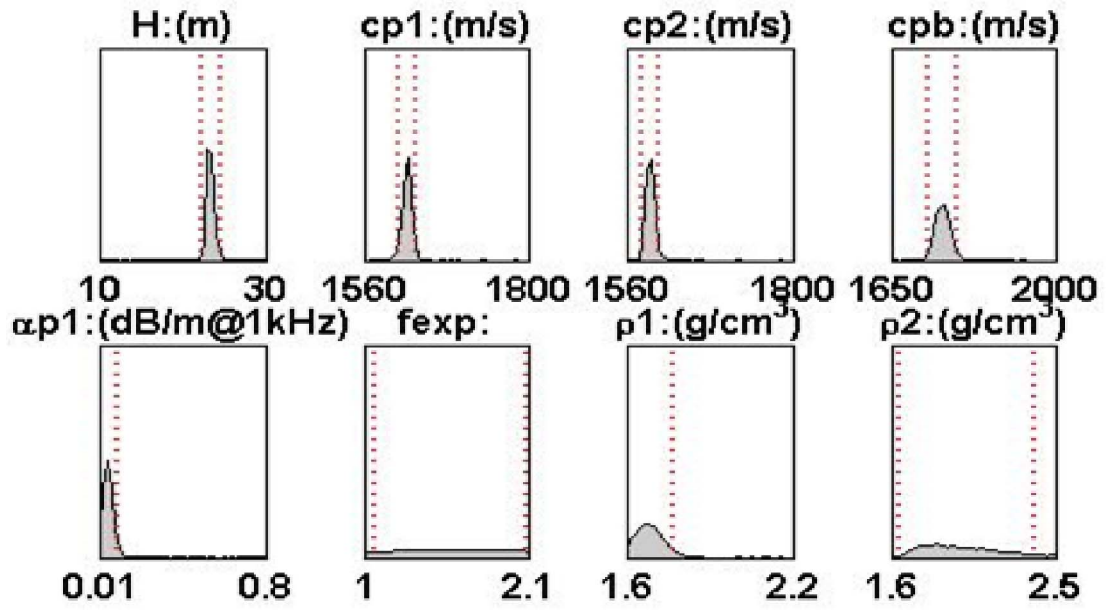


Figure 3(a).

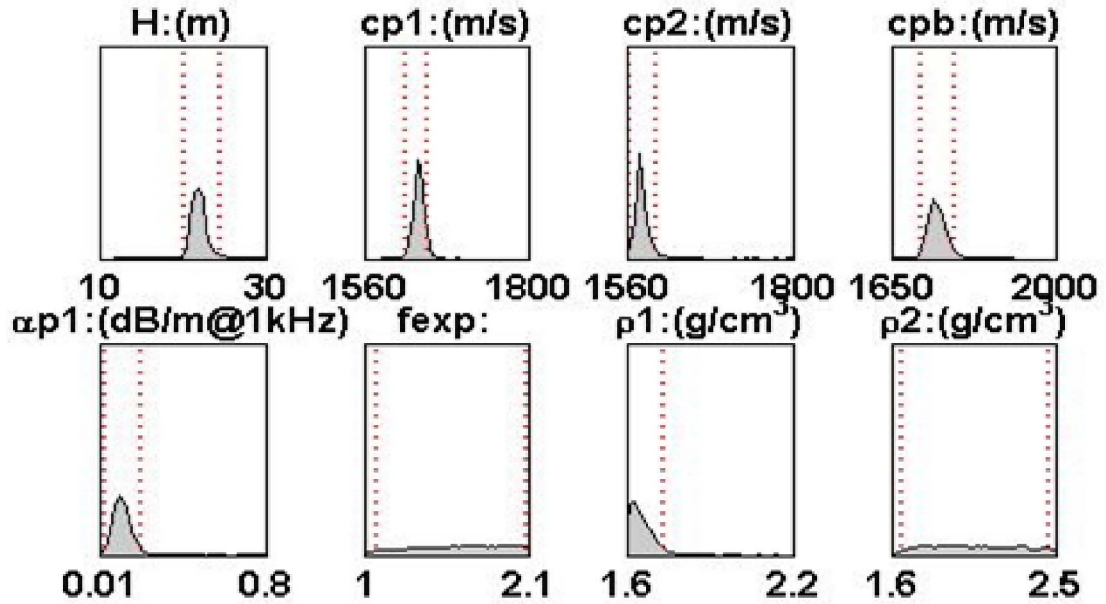


Figure 3(b). Marginal densities of the estimated geoacoustic model parameters for EOFs generated using a limited set of water column SSPs taken during the time of the measurements (a), and for a more extensive set that spanned a greater time and area (b).

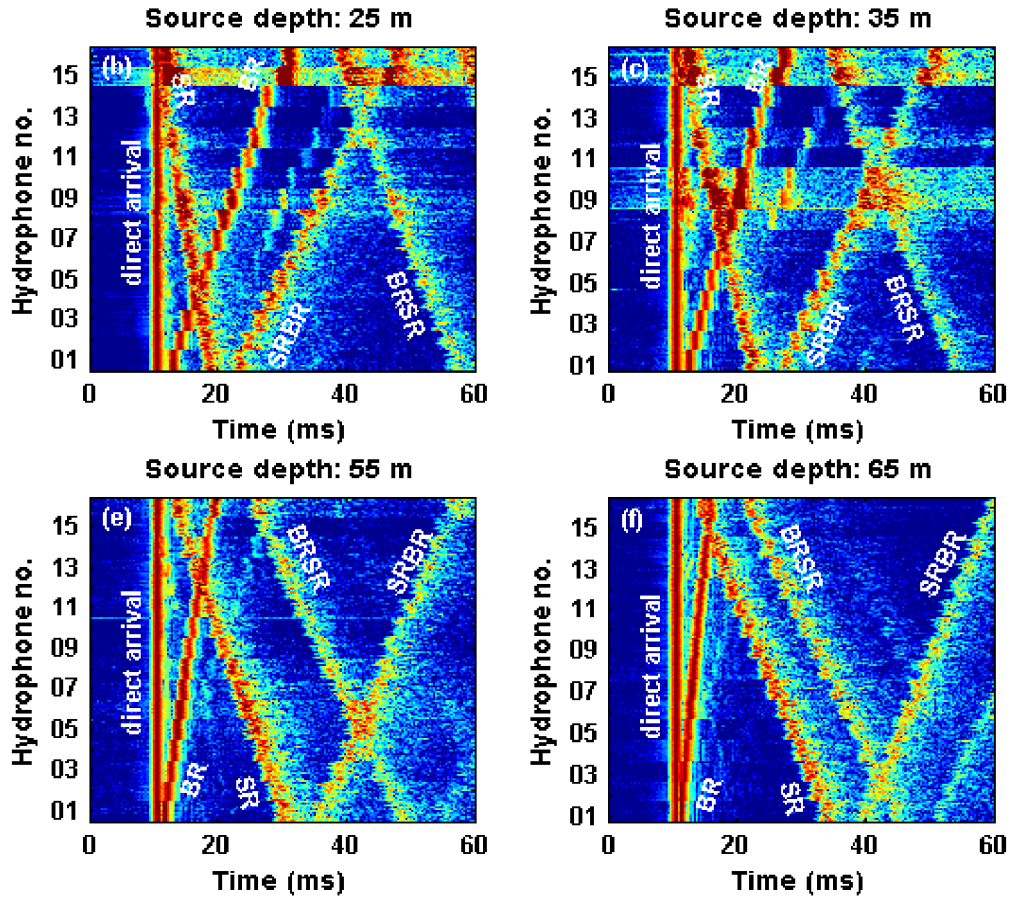


**Table 1. Travel time inversion results for one layer over half space model.**

Parameter	Source depth				
	25m	35m	45m	55m	65m
layer thickness (m)	21.5	20.6	22.3	22.3	20.4
sound speed (m/s)	1609	1597	1600	16001	1584
TWT (ms)	26.7	25.8	27.9	27.9	25.8

**Table 2. Travel time inversion results for two-layer over half space model.**

Source depth	layer I		layer II	
	sound speed	layer thickness	sound speed	layer thickness
55m	1581m/s	11.9m	1602m/s	9.1m
65m	1584m/s	14.5m	1611m/s	8.4m



**Figure 4. Matched filtered signal for mid frequency LFM sweep data.**



## **IMPACT/APPLICATIONS/TRANSITIONS**

The research demonstrated that the uncertainties in the water column can have significant impact on the performance of matched field geoacoustic inversion. The results of the inversion showed that uncertainty in the water column can be accounted for using an averaged sound speed profile defined by empirical orthogonal functions that are estimated in the inversion. For sound speed variations that are not large, it is sufficient to use a limited set of measured SSPs that contain the variations in the sound speed profile that are characteristic of the variations at the time of the experiment.

## **RELATED RESEARCH**

The experimental data from the SW06 geoacoustic experiments are high quality data that can serve as benchmark data for evaluating the performance of geoacoustic inversion methods. My research related to the analysis and interpretation of data from the geoacoustic experiments in SW06 is connected with the research projects of the following: W. S. Hodgkiss and P. Gerstoft (MPL, SCRIPPS); D. Knobles (ARL:UT); G.V. Frisk (Florida Atlantic); K. Becker (ARL Penn State); P. Dahl and D.J. Tang (APL UW); J. Miller (University of Rhode Island), J. Goff, U of Texas at Austin and J. Lynch (WHOI). The overall goal of this group is to apply geoacoustic inversion techniques to data that were obtained at the site near the MPL vertical line array and along the radial track from it. Comparison of the results from the different techniques will provide new understanding of the strengths and limitations of present day inversion techniques.

## **REFERENCES**

- Chapman, N.R., ChinBing, S., King, D. and Evans, R.B., Benchmarking geoacoustic inversion methods for range dependent waveguides, *IEEE J. Oceanic Eng.*, **28**, 320-330 (2003).
- Choi, J.W., P. Dahl and J. A. Goff, Observations of R-reflector and sediment interface reflection at the Shallow Water '06 central site, *JASAEL*, EL128-EL134, (2008).
- Yong-Min Jiang, N. Ross. Chapman and Mohsen Badiy, "Quantifying the uncertainty of geoacoustic model parameters for the New Jersey shelf by inverting air gun data," *J. Acoust. Soc. Am.* **121**, 1879-1895 (2007)
- Jie, Y., Dajun Tang, and Kevin L. Williams, Direct measurement of sediment sound speed in Shallow Water '06, *JASA EL*, EL116-EL121, 2008.
- Morley, M., S. Dosso and N.R. Chapman, Effects of neglected seabed range dependence in geoacoustic inversion, Accepted in *IEEE J. Oceanic Eng.*, 2008.
- Turgut, A. and T. Yamamoto, In situ measurement of velocity dispersion and attenuation in New Jersey Shelf sediments, *JASAEL*, EL122-EL127, (2008).

## **PUBLICATIONS**

- Yong-Min Jiang, N. Ross. Chapman and Mohsen Badiy, Quantifying the uncertainty of geoacoustic model parameters for the New Jersey shelf by inverting air gun data, *J. Acoust. Soc. Am.* **121**, 1879-1895 (2007).

Yong-Min Jiang, N. Ross. Chapman, Bayesian Geoacoustic Inversion in a Dynamic Shallow Water Environment, J. Acoust. Soc. Am. 123, EL155, (2008).

Yong-Min Jiang, N. Ross. Chapman and P. Gerstoft, Short range travel time geoacoustic inversion with vertical line array, J. Acoust. Soc. Am. 124, EL135, (2008).

Chapman, N. R and Jiang, Y-M, Inference of ocean bottom properties by geoacoustic inversion, in *Elements in Geoacoustic inversion, Signal Processing and Reverberation in Underwater Acoustics*, edited by A. Tolstoy, Research Signpost, India, pp55-78, (2008).